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(57) Abstract

Superconducting electromagnet apparatus comprises a main coil assembly (1) and a main current supply (5) energising and de-energising the main coil assembly (1), and for persisting the current flow in the main coil assembly (1) when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in a working volume. The apparatus further comprises a B0 shim coil assembly (2) comprising superconducting shim coils connected within a closed loop and arranged to magnetically couple with the main coil assembly (1) and an auxiliary current supply (6) for supplying current to the closed loop, and for persisting the current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field. A control circuit (31, 38) is provided for controlling the main and auxiliary current supplies (5, 6) and the main coil assembly (1), the B0 shim coil assembly (2) and the control circuit (31, 38) are adapted to at least partly compensate for the effect of variation of the magnetic field within the working volume with time. In this case the shim coil assembly performs both the function of a B0 shim and at the same time compensates for the effect of variation of the magnetic field within the working volume with time, thus avoiding the need to provide individual closed loop coil assemblies for performing these functions separately which would result in functional difficulties due to inductive coupling between these auxiliary coil assemblies.

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"Superconducting Electromagnet Apparatus"

This invention relates to superconducting electromagnet apparatus. Such apparatus can be used in various applications including nuclear magnetic resonance (NMR) spectroscopy and imaging and Fourier-transform mass spectrometry (FTMS).

In conventional superconducting electromagnet apparatus a main superconducting coil assembly of cylindrical form is used to produce a central magnetic field which varies very little over a specified working volume within the bore of the cylinder, that is the so-called homogeneity volume. In many applications of such apparatus, it is necessary for a precise value of the central magnetic field to be set. Furthermore it is often necessary or desirable to make a fine adjustment to this central magnetic field value, for example to reset the central magnetic field to the specified value after it has been altered by use of a passive or superconducting shim coil assembly (which is used to achieve the optimum degree of homogeneity within the homogeneity volume but which can sometimes lead to a slight change in the central magnetic field value). Ideally this fine adjustment should be made without any degradation of the magnetic field homogeneity within the homogeneity volume.

It is known to make use of a so-called B0 shim coil assembly to provide fine adjustment of the central magnetic field value with minimal degradation of the magnetic field homogeneity within the homogeneity volume. Such a B0 shim coil assembly comprises a plurality of superconducting coils connected in series to form a closed loop which is electrically separate from the main superconducting coil assembly but which couples magnetically with the main coil assembly. The B0 shim coils are wound on an outer former which surrounds an inner former on which the main coils are wound and within which the homogeneity volume is located. The B0 shim coil assembly also incorporates a superconducting switch within the loop and current input terminals for adjusting the amount of current passing through the shim coils and for enabling persistence of this current when the required current value is reached and the superconducting switch is closed, the required current value being zero or a positiv or

negative value. The geometries of the B0 shim coils are chosen so as to have substantially no effect on the homogeneity of the magnetic field within the homogeneity volume. Furthermore the B0 shim coils are constructed using materials such that the maximum required operating current is well below the critical current at which the coils are no longer superconducting and such that there is insignificant drift in the magnetic fields associated with these coils. Thus, in the persisted mode in which the uniform central magnetic field is maintained within the homogeneity volume, the current in the shim coils will remain substantially unchanged ignoring the effect of any inductive interactions with any other part of the electromagnet apparatus or with any external field source. Typically the shim coils are constructed using wire having a critical current of the same order of magnitude as the wire used for the main magnet coils.

In most circumstances the coupling of the B0 shim coil assembly with other shim coil assemblies, which are provided to correct distortions in the magnetic field due to other disturbing influences, is minimal. This can be ensured by appropriate choice of the shim coil geometries. As is well known the superconducting switch of the B0 shim coil assembly can be operated in the same manner as the superconducting switch which is provided for controlling the main coil assembly. In both cases, after the coils have been charged to the required current level from an external current source whilst the loop is open-circuited by opening of the switch, the switch is closed to allow the required constant current level to be maintained within the superconducting loop incorporating the coils. Where the main coil assembly is being initially energised, such switching of the switches associated with the main coil assembly and the B0 shim coil assembly can be effected in series. However, when the main coil assembly is in the persisted mode, switching of the B0 shim coil assembly must be effected independently of the main coil assembly to provide the required fine adjustment of the central magnetic field.

In addition to the ability to set the central magnetic field to a precise desired value, it is important in many applications that this set value remains stable with time. For example, in NMR spectroscopy, experiments conducted within the apparatus can last over several days and even small variations in the value of the central magnetic

field, for example of the order of a few parts per billion, can lead to systematic differences in the spectral results obtained as a result of such experiments. There are essentially two ways in which the central magnetic field value can exhibit time-dependence, that is either as a result of a change in the ambient magnetic field due to external sources, or as a result of variation in the magnetic field generated by the main coil assembly itself.

WO 89/09475 discloses a superconducting electromagnet apparatus which makes use of an assembly of auxiliary coils which magnetically couple to the main coil assembly in order to reduce the effect of variation of the central magnetic field value due to changes in the ambient magnetic field. In such apparatus an assembly of superconducting shielding coils connected in series within a loop is arranged so that the effective areas and mutual and self inductances of the main coils and the shielding coils are such that any change in the ambient magnetic field causes changes in the currents of the main coils and the shielding coils in such a manner as to generate a change in the central magnetic field which opposes the change in the central magnetic field due to the change in the ambient magnetic field alone. The main coil assembly would itself usually partially shield the homogeneity volume from the effect of such changes in the ambient magnetic field even without the use of such shielding coils, but the shielding effect can be significantly increased by the use of the shielding coils.

Furthermore EP 0468425A discloses an active-shield superconducting electromagnet apparatus comprising a first superconducting coil assembly for generating a first magnetic field, and a second superconducting coil assembly for generating a second magnetic field, the second coil assembly being electrically connected in series with the first coil assembly and the two assemblies being arranged such that a resultant, uniform magnetic field is generated in the working volume and the second magnetic field opposes the first magnetic field externally of the apparatus so that the stray magnetic field outside the coil assemblies is very small. This enables personnel to work safely relatively close to the apparatus without requiring an excessive amount of cumbersome and expensive iron shielding.

However the automatic shielding arrangement of WO 89/09475 is no longer effective in relation to conventional active-shield superconducting electromagnet apparatus. Accordingly EP 0468425A proposes an arrangement in which screening coils connected within a closed loop are provided having a number of turns at least an order of magnitude less than the number of turns in the first and second coil assemblies so as to reduce the effect of disturbing influences on the central magnetic field whilst having an insignificant effect on the homogeneity of the central magnetic field. In this case the screening coils are wound from superconducting wire having a critical current such that they revert to the normal conducting state during quenching of the first and second coil assemblies. In this way the maximum contribution which the screening coils can make to the stray magnetic field is rendered insignificant. Furthermore the number of turns of the screening coils is so small that it is a straightforward matter to generate current in the screening coils to provide adequate screening capacity without risk of generating significant stray magnetic field.

With regard to the second effect producing variation of the central magnetic field value over time, that is variation of the magnetic field generated by the main coil assembly itself as a result of variation of the current supplied to the coil assembly, this effect can be caused by the properties of the superconducting wire which is used to wind the coils and which can result in a very slow decrease in the current (typically several parts per billion per hour of the operating current value) in a phenomenon known as "drift". It is possible to model such drift in terms of an effective residual resistance of the main coils, and to compensate for the drift on the basis of this relationship. The compensating of drift in this way is referred to as "locking". However, in order for such compensation to be effective, it is important that the drift of the current in the compensating coils is insignificant by comparison with the drift of the current in the main coils. Since the effective residual resistance increases significantly as the operating current in the coils becomes comparable with the critical current value of the wire used for winding the coils, this requires the critical current value for a given maximum current in the compensating coils to be greater than a particular minimum value.

Furthermore the conventional B0 shim coil assembly as described above actually has the effect of increasing the rate of change of the central field due to the drift of the current in the main coil assembly.

It is an object of the invention to provide superconducting electromagnet apparatus with a B0 shim coil assembly which, as well as providing fine adjustment of the central magnetic field value, also compensates for changes in the central magnetic field value with time either as a result of changes in the ambient magnetic field or as a result of changes in the field generated by the main coil assembly itself, or as a result of both such effects.

According to the present invention there is provided superconducting electromagnet apparatus comprising a main coil assembly, main current supply means connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in a working volume, a B0 shim coil assembly comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly, auxiliary current supply means connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means for controlling the main and auxiliary current supply means, wherein the main coil assembly, the B0 shim coil assembly and the control means are adapted to at least partly compensate for the effect of variation of the magnetic field within the working volume with time.

It will be appreciated that the invention provides an arrangement by which a single closed loop coil assembly can perform the function of a B0 shim whilst at the same time compensating for the effect of variation of the magnetic field within the

working volume with time. The coil assembly may be adapted to compensate for the effect of time variation of the magnetic field as a result of time variation of the ambient magnetic field, or alternatively may be adapted to compensate for the effect of time variation of the magnetic field as a result of drift of the current in the main coil assembly. As a further alternative the shim coil assembly may be adapted to compensate for both of these time-varying effects. However in all cases the single closed loop coil assembly serves several functions, and thus avoids the need to provide individual closed loop coil assemblies for performing these functions separately which would result in functional difficulties in view of the fact that each such auxiliary coil assembly would couple inductively with the other auxiliary coil assemblies as well as with the main coil assembly. Furthermore the provision of separate auxiliary coil assemblies for performing the different functions individually would result in additional complications in the design and construction of the apparatus, as well as rendering the apparatus more expensive than apparatus in accordance with the invention in which a single closed loop coil assembly is adapted to perform more than one function simultaneously, that is the above-described shielding and/or locking functions in addition to the fine adjustment of the central magnetic field value.

In order that the invention may be more fully understood, superconducting electromagnet apparatus in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a first embodiment of the invention;

Figure 2 is a further schematic diagram showing the positions and sizes of individual coils within the first embodiment;

Figure 3 is a block diagram of a control system for such apparatus; and

Figures 4 and 5 are schematic diagrams of a second embodiment of the invention.

A description will now be given of a particular form of superconducting electromagnet apparatus in accordance with the invention for use in a particular NMR spectroscopy application in which a central magnetic field of high homogeneity and high constancy with respect to time is generated. However it should be appreciated that the design of such apparatus is dictated by the particular application in which it is to be used, and that different designs of apparatus in accordance with the invention are required for other applications. Furthermore the description of such apparatus omits a description of those features which are already well known in the art, such as the particular method of fabrication of the coils and details of the associated radiation shielding and cooling arrangements.

Referring to Figure 1 the superconducting electromagnet apparatus comprises a cylindrical main coil assembly consisting of main coils 1 connected in series within a closed loop 1a including a superconducting switch 3 having a heating element and electrical connections 5 for the supply of drive current to the main coils from an external current source (not shown). The superconducting switch 3 is also provided with electrical connections 7 for the supply of current to the heating element of the switch 3. Furthermore a B0 shim coil assembly is provided in the form of B0 shim coils 2 connected in series within a closed loop 2a including a superconducting switch 4 having a heating element and electrical connections 6 for supply of drive current to the B0 shim coils from an external current source (not shown). The superconducting switch 4 is also provided with electrical connections 8 for the supply of current to the heating element of the switch 4.

Figure 2 diagrammatically shows an upper axial section through the apparatus. It will be appreciated that the lower axial section is not shown in order to render the figure easier to read, but that this is similar to the upper axial section, and that in practice each of the coils and formers shown in the figure are of cylindrical form surrounding an axial bore 9 defining the working volume of the magnet. Referring to Figure 2 the main coil assembly comprises two main magnet coils 11 and 12 wound on an inner cylindrical aluminium former 10 (shown in broken lines in the figure). The current circulating through the two main magnet c ils 11 and 12 provides most of the

central magnetic field, but the magnetic field produced by these coils would not be homogeneous enough for NMR spectroscopy applications without the provision of further compensating coils. Accordingly smaller compensating coils 13, 14, 15 and 16 are wound on a further cylindrical aluminium former 20 (also shown in broken lines in the figure) which is coaxial with, and surrounds, the inner former 10. The purpose of the smaller compensating coils 13 to 16 is to correct for most of the lowest order axial inhomogeneities introduced by the main magnet coils 11 and 12. The coils 11 to 16 are connected in series within a closed loop and are supplied with current in a manner already described above.

The design of the B0 shim coil assembly follows broadly similar principles to ensure that it produces a largely homogeneous central magnetic field contribution within the homogeneity volume. To this end the B0 shim coil assembly comprises a long solenoid coil 17 wound on the inner former 10 between the coils 11 and 12, and two smaller coils 18 and 19 wound on top of the coils 13 and 14 on the former 20 and designed to substantially cancel the lowest order inhomogeneities that would be produced by the coil 17 alone. The coils 17, 18 and 19 are connected in series within a closed loop and are supplied with current in a manner already described above. The positions of the coils 17, 18 and 19, and the numbers of turns in each coil, are chosen so that the effective B0 strength is suitable for the specific application and such as to produce favourable locking and shielding effects. In particular the central coil 17 should be positioned close to the working volume in order to provide the required locking effect. It should be noted that, since the central coil 17 is wound on the same former 10 as the main coils 11 and 12, the three coils are potted together, that is embedded within the same integral block of wax or other potting material. An outer former 30 (also shown in broken lines in the figure) is provided for the other (conventional) superconducting shim coils 29 for optimising the homogeneity of the central magnetic field within the homogeneity volume.

Figure 3 shows a block circuit diagram of the current supply and control system for such apparatus. A power supply 31 is provided for supplying and controlling current to the B0 shim coil assembly 32, and additionally for controlling the supply of

current from a current source 34 to the heating element of the superconducting switch 33 of the B0 shim coil assembly. Furthermore a power supply 38 is provided for the supply and control of current to the main coil assembly 35, as well as for controlling the supply of current from a current source 32 to the heating element of the superconducting switch 36 of the main coil assembly.

When the main magnet switch 36 is opened, the B0 shim coil switch 33 is also normally held open, the ability to control the current sources 37 and 34 serially being indicated schematically by an arrow connecting the source 37 to the source 34. In one possible arrangement the B0 shim coil switch 33 opens automatically if the main magnet develops a voltage across it above a certain threshold, for example in quench conditions or if the main coil switch 36 is open. This protects the B0 shim coil assembly 32 from damage which might otherwise result from the large current produced by inductive coupling to the main coil assembly 35 if the main coil assembly were to quench or the main coil switch were to open. It is also possible to control the B0 shim coil switch independently of the power supply 31 as shown by the arrow 39.

The specific coil geometry for both the main coil assembly and the B0 shim coil assembly in a particular example is indicated in Table 1 below. From this geometry, the effective areas for the two circuits can be calculated, and in turn the current/field ratios and the self and mutual inductances can be derived. These are given in Table 2 below. Using these parameters in equations 4, 6 and 10 of the theoretical summary set out below yields an effective B0 strength of 1.4 mT/A, a shielding factor to external influences of approximately 6, and a locking factor for central magnetic field drift of approximately 6.7.

coil	mean radius (cm)	width (cm)	turns
11	4.58	33.00	7330
12	5.76	33.00	21146
13	7.17	4.70	1066
14	7.03	0.20	18
15	7.17	4.70	1066
16	7.03	0.20	18
17	5.01	33.00	3662
18	7.43	4.70	103

		10	
19	7.43	4.70	103

Table 1: Geometry of particular example

Mutual inductance of main magnet and B0	2.98 H
Self inductance of main magnet	25.88 H
Self inductance of B0 shim	0.3892 H
Effective area of main magnet	307.3 m^2
Effective area of B0 shim	32.4 m^2
Strength of main magnet	1.06E-01 T/A
Strength of B0 shim alone	1.36E-02 T/A

Table 2: Calculated parameters of particular example

It should be appreciated that various modifications of this basic design are possible within the scope of the invention. For example the main coil assembly may include coils wound in either sense and may comprise a mixture of coils with some of the coils being wound in one direction and other coils being wound in the opposite direction. In particular the main coil assembly may be arranged to provide active screening as described above. Furthermore the B0 shim coil assembly may also include coils wound in either sense and may comprise a mixture of coils wound in one direction and coils wound in the opposite direction.

Although the B0 shim coils 17, 18 and 19 are described as separately wound coils in the description with reference to Figure 2, it should be appreciated that it would also be possible for some or all of the windings of the B0 shim coil assembly to be constituted by parts of the main coil assembly, so that these parts of the main coil assembly would form parts of both the main magnet circuit and the B0 shim coil circuit and would carry current from both circuits. The incorporation of all or part of the B0 shim coil assembly in the main coil assembly may be advantageous in certain circumstances, and may provide a simpler and less costly construction.

Figure 4 is a diagram, similar to that of Figure 1, showing a second embodiment of the invention in which the B0 shim coils 2' are constituted by parts of the main coils 1'. In Figure 4 like reference numerals denote the same parts as in Figure 1.

Furthermore Figure 5 diagrammatically shows the connections between the coils in this second embodiment in more detail, the coils consisting of two main magnet coils 11' and 12', smaller compensating coils 13', 14', 15' and 16' and the B0 shim coils 17', 18' and 19' having similar functions to the corresponding coils 11-19 shown in Figure 2. Apart from the fact that the B0 shim coils 17, 18 and 19 form parts of the main coil assembly, the construction of this second embodiment is similar to that of the first embodiment.

Theoretical basis

The following description provides what is believed to be a reasonable theoretical basis for the design of superconducting electromagnet apparatus in accordance with the invention in which a single coil assembly performs the three functions of a B0 shim, shielding and locking.

The main properties of a combined B0 shim/shielding/locking coil assembly can be deduced from three basic equations governing the main magnet/shim interactions.. Equations 1 and 2 represent Faraday's law of induction applied to the main coil assembly and shim coil assembly respectively, and equation 3 is related to Ampère's law.

1. $$-\frac{d\phi_m}{dt} = A_m \frac{dB_{ext}}{dt} = -L_m \frac{dI_m}{dt} - M\frac{dI_s}{dt} + I_m R_m$$

2. $$-\frac{d\phi_s}{dt} = A_s \frac{dB_{ext}}{dt} = -L_s \frac{dI_s}{dt} - M\frac{dI_m}{dt} + I_s R_s + \varepsilon_s$$

3. $$\frac{dB}{dt} = S_m \frac{dI_m}{dt} + S_s \frac{dI_s}{dt} + \frac{dB_{ext}}{dt}$$

In these equations the symbols represent the following:

Symbol	Meaning
A_m	Effective area of main coil assembly
A_s	Effective area of B0 shim coil assembly
B	Central magnetic field
B_{ext}	External (ambient) magnetic field
e_s	Applied emf when adjusting B0 current
I_m	Current in main coil assembly
I_s	Current in B0 shim coil assembly

L_m	Self inductance of main coil assembly
Ls	Self inductance of B0 shim coil assembly
M	Mutual inductance of main/B0 shim coil assemblies
ϕ_m	Flux linking main coil assembly
ϕ_s	Flux linking B0 shim coil assembly
R_m	Effective residual resistance of main coil assembly
R_s	Effective residual resistance of B0 shim coil assembly
S_m	Central magnetic field/current ratio for isolated main coil assembly
S_s	Central magnetic field/current ratio for isolated B0 shim coil assembly

A) If current is driven into the B0 shim coil assembly at a rate much faster than any external field changes and any internal magnet drift (i.e. in all practical cases), equation 1 gives $\Delta I_m = -(M / L_m)\Delta I_s$, which in equation 3 leads to an effective B0 strength of:

4. $$S_{B_0} \equiv \frac{\Delta B}{\Delta I_s} = S_s - \frac{M}{L_m} S_m .$$

The first term on the right-hand side of this equation is the change in the central magnetic field per amp for the isolated B0 shim coil assembly, and the second term is the effect on the central magnetic field due to the induced change in current in the main coil assembly per amp of current in the B0 shim coil assembly.

B) If the B0 shim coil assembly is in the persisted state but there are perturbations in the ambient magnetic field ($dB_{ext}/dt \neq 0$) which dominate compared to the drift of the magnet, then solving equations 1 and 2 gives:

5. $$\Delta I_s = \frac{MA_m - L_m A_s}{L_m L_s - M^2} \Delta B_{ext}$$
$$\Delta I_m = \frac{MA_s - L_s A_m}{L_m L_s - M^2} \Delta B_{ext}$$

By using equations 5 in 3, the reduction in the influence of a change in the ambient magnetic field can be shown to be:

6. $$\frac{\Delta B_{cm}}{\Delta B}=\left[1+\frac{(MA_m-L_mA_s)S_s+(MA_s-L_sA_m)S_m}{L_mL_s-M^2}\right]^{-1}.$$

The first term on the right-hand side of this equation (unity) is the change in the central magnetic field with neither the main coil assembly nor the B0 shim coil assembly present. Furthermore the first part of the second term is the change in the central magnetic field due to the current induced in the B0 shim coil assembly considered as part of the complete system, that is allowing for inductive coupling with the main coil assembly. The second part of the second term is the change in the central magnetic field due to the current induced in the main coil assembly considered as part of the complete system, that is allowing for inductive coupling with the main coil assembly.

C) If the main coil assembly is in the persisted state but there are no external perturbations to the magnetic field, then the natural magnet drift (allowed for in equations 1 and 2 by the effective resistances) will become dominant. If the B0 shim coil assembly is designed such that $I_s << I_c$ (critical current), then we can assume that $R_s \approx 0$, and equation 2 can be substituted in equation 1 to give:

7. $$\frac{1}{I_m}\frac{dI_m}{dt}=\left(\frac{M^2}{L_s}-L_m\right)^{-1}R_m$$

From this, the change in the magnetic field is found from equation 3:

8. $$\frac{dB}{dt}=\frac{I_mR_m\left(S_m-S_s\frac{M}{L_s}\right)}{\left(\frac{M^2}{L_s}-L_m\right)}$$

Without the B0 shim coil assembly the main magnet drift would be:

9. $$\frac{dB_m}{dt} = I_m S_m \times -\frac{R_m}{L_m},$$

so that the reduction in magnetic field change is given by:

10. $$\frac{\Delta B_m}{\Delta B} = \frac{\left(1-\frac{M^2}{L_m L_s}\right)}{\left(1-\frac{S_s}{S_m}\frac{M}{L_s}\right)}.$$

The denominator on the right-hand side of this equation relates to the change in the central magnetic field due to the current inductively coupled into the B0 shim coil assembly relative to the change in the central magnetic field due to the current inductively coupled out of the main coil assembly. The numerator relates to the effect which the inductive coupling of the two coil assemblies has on the rate of change of current in the main coil assembly.

It will be appreciated that equations 4, 6 and 10 above can be applied to determine the optimum geometries and positioning of the main coil assembly and B0 shim coil assembly in order to provide the required locking and/or shielding in addition to the conventional B0 shim function of the B0 shim coil assembly. The effect of moving a coil (the coil 17 in Figure 2) of the B0 shim coil assembly further towards the magnet bore is to increase S_s but to decrease A_s, and this can result in an increase in the locking effect, although in some cases it can also lead to a decrease in the shielding effect.

CLAIMS:

1. Superconducting electromagnet apparatus comprising a main coil assembly (1; 1'), main current supply means (5) connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in a working volume, a B0 shim coil assembly (2; 2') comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly (1; 1'), auxiliary current supply means (6) connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means (31, 38) for controlling the main and auxiliary current supply means (5, 6), wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to at least partly compensate for the effect of variation of the magnetic field within the working volume with time.

2. Apparatus according to claim 1, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the ambient magnetic field with time.

3. Apparatus according to claim 1 or 2, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the current flow in the main coil assembly with time.

4. Apparatus according to claim 1, 2 or 3, wherein the B0 shim coil assembly (2; 2') is constructed from a material having a critical current value, at which the B0 shim coil assembly would revert to the normal conducting state, which is significantly

greater than the value of the current required to compensate for time variation of the magnetic field within the working volume.

5. Apparatus according to any preceding claim, wherein the B0 shim coil assembly (2; 2') incorporates at least one coil wound on the same former as at least one coil of the main coil assembly.

6. Apparatus according to any preceding claim, wherein the auxiliary current supply means (6) incorporates a superconducting switch (4) including a heating element for heating the switch (4) to drive it out of its superconducting state to cause the current passing through the switch (4) to decay.

7. Apparatus according to any preceding claim, wherein the main current supply means (5) incorporates a superconducting switch (3) including a heating element for heating the switch (3) to drive it out of its superconducting state to cause the current in the main coil assembly (1; 1') to decay.

8. Apparatus according to any preceding claim, wherein the auxiliary current supply means (6) includes input terminals to which current is supplied under control of the control means (31) during initial energisation of the B0 shim coil assembly (2; 2'), such current supply to the input terminals being terminated when the current flowing in the closed loop has reached the desired level.

9. Apparatus according to any preceding claim, wherein the main coil assembly (1; 1') comprises a plurality of superconducting main coils connected in series within a closed loop.

10. Apparatus according to any preceding claim, wherein the main coil assembly (1; 1') comprises at least one coil wound in one direction and at least one other coil wound in the opposite direction.

11. Apparatus according to any preceding claim, wherein the B0 shim coil assembly (2; 2') comprises a plurality of superconducting shim coils connected in series within a closed loop.

12. Apparatus according to claim 11, wherein at least one of the coils of the B0 shim coil assembly (2; 2') is constituted by part of the main coil assembly.

13. Apparatus according to any preceding claim, wherein the B0 shim coil assembly (2; 2') comprises at least one coil wound in one direction and at least one other coil wound in the opposite direction.

14. Apparatus according to any preceding claim, wherein at least one further shim coil assembly (29) is provided for adjustment of the degree of homogeneity of the central magnetic field.

09/914416

WO 00/52490 PCT/GB00/00658

Fig. 1

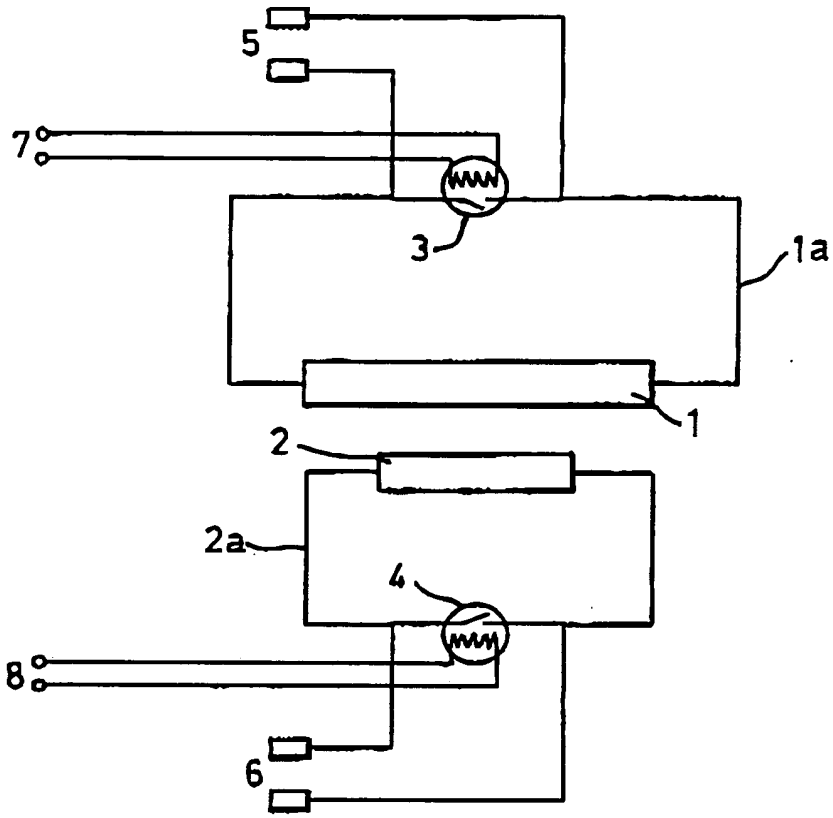

Fig. 2

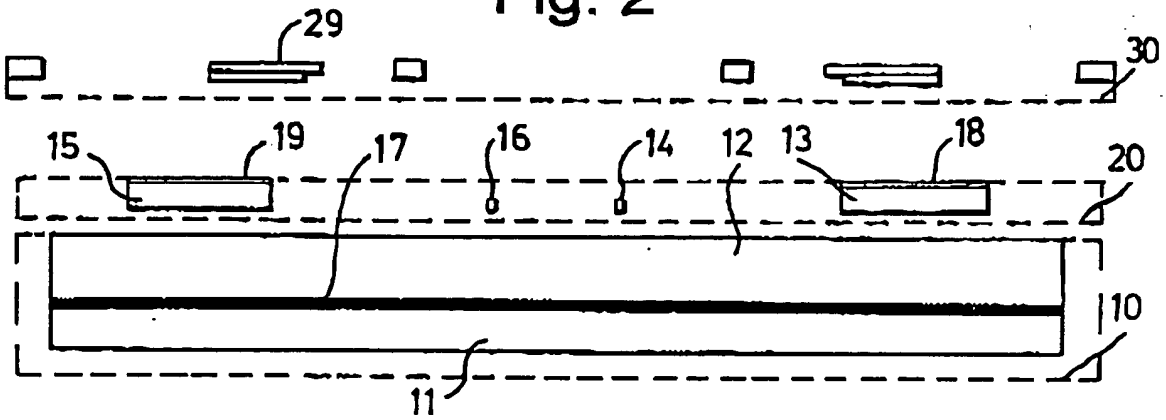

Fig. 3

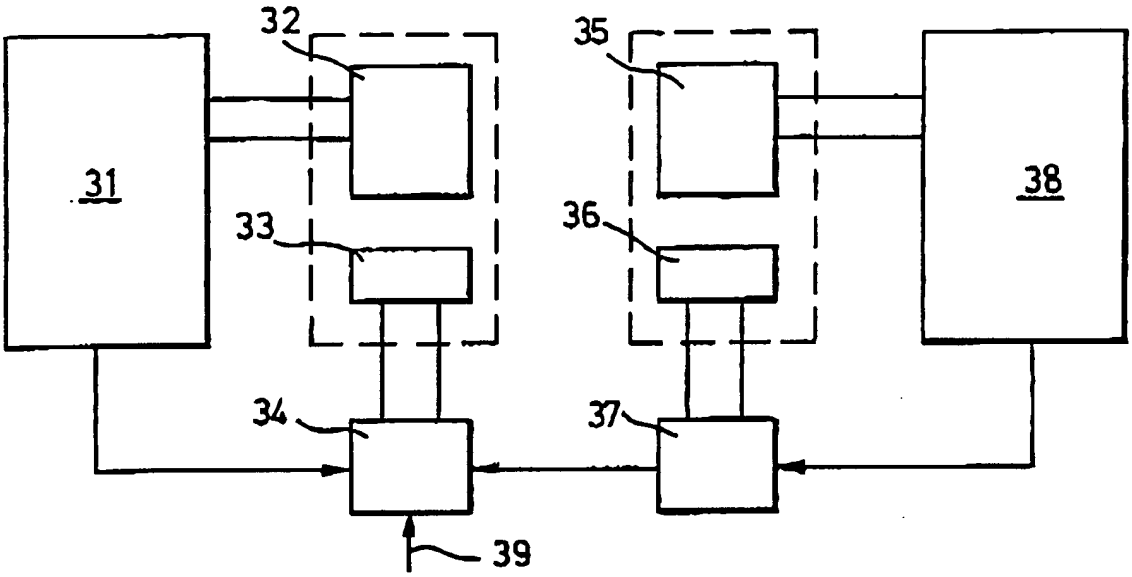

Fig. 4

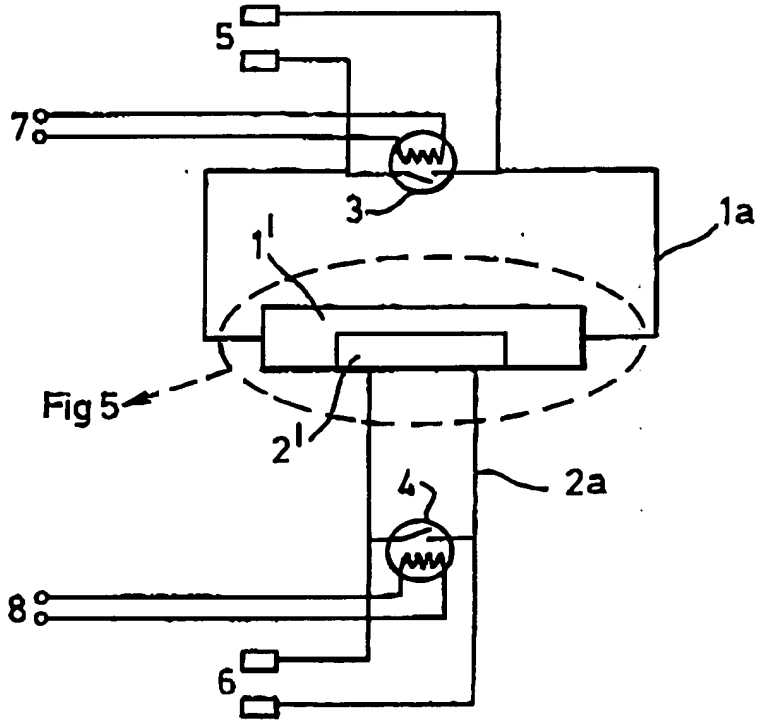

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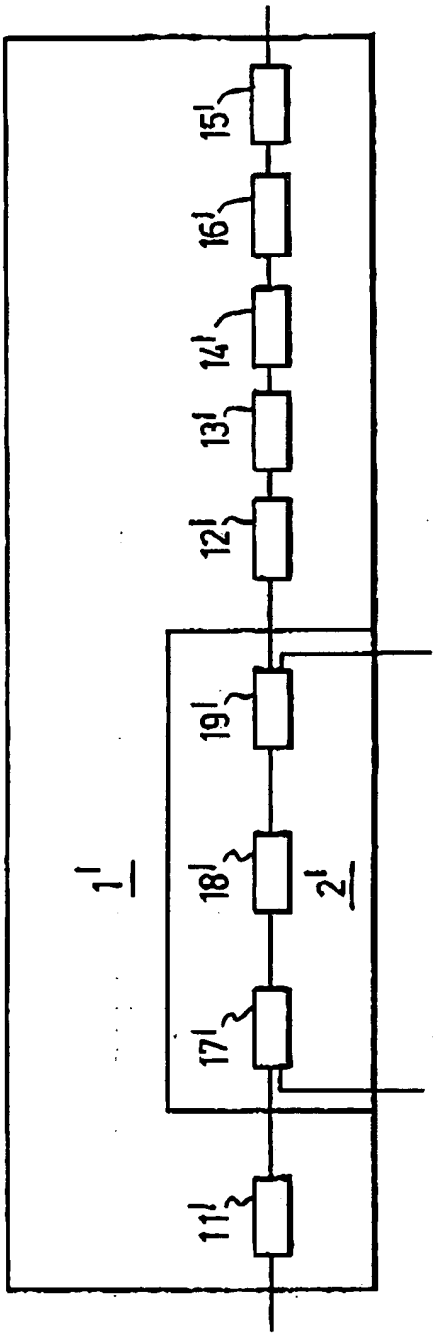
Fig. 5



INTERNATIONAL SEARCH REPORT

Inter. nal Application No
PCT/GB 00/00658

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01R33/3815 H01F6/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01R H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 713 722 A (E. TOYODA, S. HAYASHI) 15 December 1987 (1987-12-15) column 1, line 8 -column 10, line 24 figures 1-7	1-3,5-9, 11,12,14
X	PATENT ABSTRACTS OF JAPAN vol. 10, no. 35 (E-380), 12 February 1986 (1986-02-12) & JP 60 194504 A (MITSUBISHI DENKI KK), 3 October 1985 (1985-10-03) abstract	1,2,8
X	US 4 945 446 A (SH. KURODA, M. TAKECHI) 31 July 1990 (1990-07-31) column 1, line 7 - line 13 column 4, line 8 -column 6, line 12 figures 1-5	1,2,5-7, 9,11,12, 14

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2000	31/05/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Volmer, W

1

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter nal Application No
PCT/GB 00/00658

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4713722 A	15-12-1987	DE 3675841 D	10-01-1991
		EP 0211551 A	25-02-1987
		JP 62276806 A	01-12-1987
JP 60194504 A	03-10-1985	JP 1664796 C	19-05-1992
		JP 3026530 B	11-04-1991
US 4945446 A	31-07-1990	JP 1763965 C	28-05-1993
		JP 4053086 B	25-08-1992
		JP 64000714 A	05-01-1989
		DE 3821258 A	05-01-1989
		GB 2207762 A,B	08-02-1989

09/914416

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

To:

HARDING,Richard Patrick
MARKS & CLERK
4220 Nash Court
Oxford Business Park South
Oxford 0X4 2RU
GRANDE BRETAGNE

RECEIVED
14 JUN 2001
MARKS AND CLERK

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL PRELIMINARY EXAMINATION REPORT
(PCT Rule 71.1)

Date of mailing *(day/month/year)*	12.06.2001
Applicant's or agent's file reference: RPH.P50566PC	**IMPORTANT NOTIFICATION**

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/GB00/00658	24/02/2000	27/02/1999

Applicant: MAGNEX SCIENTIFIC LTD. et al.

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.

2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.

3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. **REMINDER**

The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices) (Article 39(1)) (see also the reminder sent by the International Bureau with Form PCT/IB/301).

Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

For further details on the applicable time limits and requirements of the elected Offices, see Volume II of th PCT Applicant's Guide.

Name and mailing address of the IPEA/

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NL-2280 HV Rijswijk - Pays Bas
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Authorized officer

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PATENT COOPERATION TREATY 09/914416

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
RPH.P50566PC		
International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/GB00/00658	24/02/2000	27/02/1999
International Patent Classification (IPC) or national classification and IPC G01R33/3815		
Applicant MAGNEX SCIENTIFIC LTD. et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 8 sheets, including this cover sheet.

   ☐ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of sheets.

3. This report contains indications relating to the following items:

   - I ☒ Basis of the report
   - II ☐ Priority
   - III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - IV ☐ Lack of unity of invention
   - V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   - VI ☐ Certain documents cited
   - VII ☒ Certain defects in the international application
   - VIII ☒ Certain observations on the international application

Date of submission of the demand	Date of completion of this report
24/08/2000	12.06.2001
Name and mailing address of the international preliminary examining authority: European Patent Office - P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Tx: 31 651 epo nl Fax: +31 70 340 - 3016	Authorized officer Volmer, W Telephone No. +31 70 340 3516

Form PCT/IPEA/409 (cover sheet) (January 1994)

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/GB00/00658

I. Basis of the report

1. With regard to the **elements** of the international application *(Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17))*:
Description, pages:

1-4,6-14	as originally filed			
5,5a	as received on	06/04/2001	with letter of	02/04/2001

Claims, No.:

5-14	as originally filed			
1-4	as received on	06/04/2001	with letter of	02/04/2001

Drawings, sheets:

1/5-5/5	as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

   These elements were available or furnished to this Authority in the following language: , which is:

   - ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
   - ☐ the language of publication of the international application (under Rule 48.3(b)).
   - ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

   - ☐ contained in the international application in written form.
   - ☐ filed together with the international application in computer readable form.
   - ☐ furnished subsequently to this Authority in written form.
   - ☐ furnished subsequently to this Authority in computer readable form.
   - ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
   - ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/GB00/00658

4. The amendments have resulted in the cancellation of:

   ☐ the description, pages:
   ☐ the claims, Nos.:
   ☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

   (Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims 3 - 14
	No:	Claims 1, 2
Inventive step (IS)	Yes:	Claims
	No:	Claims 3 - 14
Industrial applicability (IA)	Yes:	Claims 1 - 14
	No:	Claims

2. Citations and explanations
   see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET

International application No. PCT/GB00/00658

R Item V

Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

Reference is made to the following documents:

D1: US-A-4 713 722;

D2: JP-A-60194504 [as published in Patent Abstracts of Japan; vol. 10, no. 35 published on 12-02-1986].

The present application does not satisfy the criterion set forth in Article 33(2) PCT because the subject-matter of claims 1 and 2 is not new in respect of the prior art as defined in the regulations [Rule 64(1) - (3) PCT]:

Document D1 discloses [cf. D1: col. 1, line 8 - col. 10, line 24 and the figures]:

- a superconducting electromagnet apparatus comprising:
  - a superconducting main coil assembly [reference "1" in D1, fig. 1] generating a magnetic filed of a homogenelty high enough to carry out an MRI examination and its associated current supply means for energising and de-energising the main coil assembly,
  - a superconducting shim coil assembly [reference "5" in D1, fig. 1] for providing fine adjustment of the magnetic field in the working volume with its associated current supply means for adjusting the value and the homogeneity of the main magnetic field,
  - both superconducting coil assemblies are held in the state of closed loops,
  - control means for controlling the current supply means of the main and of the shim coil assembly, both current supply means being adapted to compensate for the effect of variation of the magnetic field in the imaging volume with time [e.g.: to compensate for the effect of a timely varying magnetic field gradient which has been generated in the working volume], the control means being adapted to provide a significant compensation for the effect of said variation of the magnetic field within the working volume.

Hence, the subject-matter of claims 1 and 2 is not new.

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET International application No. PCT/GB00/00658

The present application does not satisfy the criterion set forth in Article 33(3) PCT because the subject-matter of claims 3 - 14 does not involve an inventive step [Rule 65(1) and (2) PCT]:
It is considered that these claims specify adaptations of the general construction principle that is known from D1 to the different ways of building up a superconducting electromagnet apparatus which adaptations are known and are straightforward to carry out for the person skilled in the art of electromagnet construction. Therefore, the subject-matter of claims 3 - 14 lacks an inventive step.

The objections above are due in part to the broad expression "variation of the magnetic field within the working volume with time" that is used in claim 1. In order to clearly define the object of the invention, it is suggested to draft the independent claim specifying:

- the control means are adapted to compensate for the effect of variation of th magnetic field with time within the working volume, which variation is due to the residual resistance of the superconducting coil assemblies [cf. page 4, lines 22 - 24].

However in view of the disclosures of documents D1 and D2, it is not apparent which features in the present application go beyond the disclosure of these documents. In other words, it is not clear why the compensation means of D1 or D2 could not be used to also compensate for a variation with time due to the residual resistance of the superconducting coil assemblies of the magnetic field within the working volume. Hence, the structural features in the claims can be found in D1 or D2.
Therefore, it is necessary to specify the features in the claims by a structural definition and not only by a functional definition as is presently the case. Hence, the structural features that go beyond the disclosure of D1, D2 and the other documents cited in the search report and that enable the specified result of compensating to be achieved and that enable an unambiguous delimitation with respect to these documents should have been included in the independent claim.

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET

International application No. PCT/GB00/00658

Re Item VII

Certain defects in the international application

To meet the requirements of Rule 5.1(a)(ii) PCT, the document D1 should have been identified in the description and the relevant background art disclosed therein should have been briefly discussed. Furthermore, the references of the prior art that is discussed on page 1, line 8 - page 2, line 27 should have been included in these passages.

To meet the requirements of Rule 6.3 (b) PCT, the independent claim should have been properly cast in the two part form, with those features which in combination are part of the prior art [see document D1] being placed in the preamble.

The features of the claims should have been provided with reference signs placed in parentheses (Rule 6.2(b) PCT).

INTERNATIONAL PRELIMINARY EXAMINATION REPORT - SEPARATE SHEET

International application No. PCT/GB00/00658

Re It m VIII

Certain observations on the international application

The application does not meet the requirements of Article 6 PCT for the following reasons:

The following terms or expressions used in the claims are vague and indefinite and, as such, render the scope of the claims unclear; accordingly, the claims require amendment to remove these defects [Article 6 PCT]:

- main coil assembly [claims 1, 3, 9, 10 and 12: The claims do not define the delimitation between a main coil assembly and an auxiliary coil assembly or a coil assembly that is not a main coil assembly.];

- a magnetic field of high homogeneity [claim 1: What is the delimitation between a magnetic field of high homogeneity, of low homogeneity or of a homogeneity?];

- fine adjustment of the magnetic field [claim 1: How to delimit a fine adjustment from an adjustment?];

- significantly degrading the homogeneity, significant compensation [claim 1: How to delimit a significant degradation or a significant compensation from an insignificant degradation or a degradation / an insignificant compensation or a compensation? This applies also to the term "significant" used in claim 4.].

As also stated in Section V above, the claims do not meet the requirements of Article 6 PCT in that the matter for which protection is sought is not clearly defined. The claims attempt to define the subject-matter in terms of the result to be achieved ["to provide a significant compensation for the effect of variation..."] which merely amounts to a statement of the underlying problem. These functional statement does not enable the skilled person to determine which technical features are necessary to perform the stated function. Therefore, the technical features necessary for achieving this result should have been included in the claims.

Claim 1 specifies:

- the control means being adapted to provide a "significant" compensation for the effect

of variation of the magnetic field within the working volume ... whilst maintaining the superconducting current flows in the main coil assembly and the B_0 shim coil assembly.

It is not clear how in a superconducting magnet apparatus a variation of the magnetic field can be compensated by maintaining the level of current flowing in the coils of said apparatus and generating the magnetic fields in question, as specified by:

- maintaining the superconducting current flows.

The apparent contradiction created by this specification has been ignored in Section V above.

On page 6, lines 6 - 11 the description discloses a single closed loop coil assembly constituted by the main coil assembly and by the shim coil assembly. This passage is in contradiction to the subject-matter of claim 1 which specifies a main coil assembly and a shim coil assembly which are not necessarily constituted as a single closed loop coil assembly.

Furthermore the conventional B0 shim coil assembly as described above actually has the effect of increasing the rate of change of the central field due to the drift of the current in the main coil assembly.

It is an object of the invention to provide superconducting electromagnet apparatus with a B0 shim coil assembly which, as well as providing fine adjustment of the central magnetic field value, also compensates for changes in the central magnetic field value with time either as a result of changes in the ambient magnetic field or as a result of changes in the field generated by the main coil assembly itself, or as a result of both such effects.

According to the present invention there is provided superconducting electromagnet apparatus comprising a main coil assembly (1; 1') for producing a central magnetic field in a working volume, main current supply means (5) connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the superconducting current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in the working volume, a B0 shim coil assembly (2; 2') for providing fine adjustment of the central magnetic field, the B0 shim coil assembly comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly (1; 1'), auxiliary current supply means (6) connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the superconducting current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means (31, 38) for controlling the main and auxiliary current supply means (5, 6), wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to provide significant compensation for the effect of variation of the magnetic field within the working volume with time whilst maintaining the superconducting current flows in the main coil assembly (1; 1') and the B0 shim coil assembly (2; 2').

It should be understood that the term "significant compensati n" is used in this context to denote a level of compensation which is such as to lead to a significant improvement in system performance. This would include situations where an experiment or application is achievable with such "significant compensation", whereas such an experiment or application could not be performed without such compensation.

It will be appreciated that the invention provides an arrangement by which a single closed loop coil assembly can perform the function of a B0 shim whilst at the same time compensating for the effect of variation of the magnetic field within the

CLAIMS:

1. Superconducting electromagnet apparatus comprising a main coil assembly (1; 1') for producing a central magnetic field in a working volume, main current supply means (5) connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the superconducting current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in the working volume, a B0 shim coil assembly (2; 2') for providing fine adjustment of the central magnetic field, the B0 shim coil assembly comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly (1; 1'), auxiliary current supply means (6) connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the superconducting current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means (31, 38) for controlling the main and auxiliary current supply means (5, 6), wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to provide significant compensation for the effect of variation of the magnetic field within the working volume with time whilst maintaining the superconducting current flows in the main coil assembly (1; 1') and the B0 shim coil assembly (2; 2').

2. Apparatus according to claim 1, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the ambient magnetic field with time.

3. Apparatus according to claim 1 or 2, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the current flow in the main coil assembly with time.

4. Apparatus according to claim 1, 2 or 3, wherein the B0 shim coil assembly (2; 2') is constructed from a material having a critical current value, at which the B0 shim coil assembly would revert to the normal conducting state, which is significantly

Furthermore the conventional B0 shim coil assembly as described above actually has the effect of increasing the rate of change of the central field due to the drift of the current in the main coil assembly.

It is an object of the invention to provide superconducting electromagnet apparatus with a B0 shim coil assembly which, as well as providing fine adjustment of the central magnetic field value, also compensates for changes in the central magnetic field value with time either as a result of changes in the ambient magnetic field or as a result of changes in the field generated by the main coil assembly itself, or as a result of both such effects.

According to the present invention there is provided superconducting electromagnet apparatus comprising a main coil assembly, main current supply means connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in a working volume, a B0 shim coil assembly comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly, auxiliary current supply means connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means for controlling the main and auxiliary current supply means, wherein the main coil assembly, the B0 shim coil assembly and the control means are adapted to at least partly compensate for the effect of variation of the magnetic field within the working volume with time.

It will be appreciated that the invention provides an arrangement by which a single closed loop coil assembly can perform the function of a B0 shim whilst at the same time compensating for the effect of variation of the magnetic field within the

CLAIMS:

1. Superconducting electromagnet apparatus comprising a main coil assembly (1; 1'), main current supply means (5) connected to the main coil assembly for energising and de-energising the main coil assembly, and for persisting the current flow in the main coil assembly when a desired constant current level has been reached, in order to generate a central magnetic field of high homogeneity in a working volume, a B0 shim coil assembly (2; 2') comprising superconducting shim coil means connected within a closed loop and arranged to magnetically couple with the main coil assembly (1; 1'), auxiliary current supply means (6) connected to the B0 shim coil assembly for supplying current to the closed loop, and for persisting the current flow in the closed loop when a desired constant current level has been reached, in order to provide fine adjustment of the central magnetic field within the working volume without significantly degrading the homogeneity of the central magnetic field, and control means (31, 38) for controlling the main and auxiliary current supply means (5, 6), wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to at least partly compensate for the effect of variation of the magnetic field within the working volume with time.

2. Apparatus according to claim 1, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the ambient magnetic field with time.

3. Apparatus according to claim 1 or 2, wherein the main coil assembly (1; 1'), the B0 shim coil assembly (2; 2') and the control means (31, 38) are adapted to compensate for the effect of time variation of the magnetic field within the working volume as a result of variation of the current flow in the main coil assembly with time.

4. Apparatus according to claim 1, 2 or 3, wherein the B0 shim coil assembly (2; 2') is constructed from a material having a critical current value, at which the B0 shim coil assembly would revert to the normal conducting state, which is significantly

PATENT COOPERATION TREATY

09/914416

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
RPH.P50566PC		
International application No.	International filing date *(day/month/year)*	(Earliest) Priority Date *(day/month/year)*
PCT/GB 00/ 00658	24/02/2000	27/02/1999
Applicant		
MAGNEX SCIENTIFIC LTD. et al.		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 2 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

   a. With regard to the **language,** the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.

   [ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).

   b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :

   [ ] contained in the international application in written form.

   [ ] filed together with the international application in computer readable form.

   [ ] furnished subsequently to this Authority in written form.

   [ ] furnished subsequently to this Authority in computer readble form.

   [ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.

   [ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).

3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title,**

   [X] the text is approved as submitted by the applicant.

   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract,**

   [X] the text is approved as submitted by the applicant.

   [ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is Figure No. _____

   [ ] as suggested by the applicant.

   [ ] because the applicant failed to suggest a figure.

   [ ] because this figure better characterizes the invention.

   [X] None of the figures.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/00658

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01R33/3815 H01F6/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01R H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 713 722 A (E. TOYODA, S. HAYASHI) 15 December 1987 (1987-12-15) column 1, line 8 -column 10, line 24 figures 1-7	1-3,5-9, 11,12,14
X	PATENT ABSTRACTS OF JAPAN vol. 10, no. 35 (E-380), 12 February 1986 (1986-02-12) & JP 60 194504 A (MITSUBISHI DENKI KK), 3 October 1985 (1985-10-03) abstract	1,2,8
X	US 4 945 446 A (SH. KURODA, M. TAKECHI) 31 July 1990 (1990-07-31) column 1, line 7 - line 13 column 4, line 8 -column 6, line 12 figures 1-5	1,2,5-7, 9,11,12, 14

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2000	31/05/2000

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/GB 00/00658

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